

Island Coalescence Stress: Solving a 30-Year-Old Scientific Debate

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Motivation—The effective mechanical properties of a material are highly dependent upon the residual stress state introduced during fabrication. Unfortunately, the evolution of intrinsic stress during deposition of non-epitaxial thin films is quite complex and still highly debated. The only area where there is a consensus as to the mechanism is during island coalescence, where tensile stresses have been observed to exceed one gigapascal. Existing theoretical models for coalescence stress all determine the mean tensile stress in mechanical equilibrium, as a function of island size and geometry at the moment of coalescence. However, computational necessity requires the use of highly simplified island geometries with uniform sizes and simultaneous coalescence. In real films, coalescence events are stochastically distributed in time and occur among islands with a broad range of sizes and shapes. As a result, despite models having existed for over 30 years, it has not been possible to compare them quantitatively to measurements in stochastically-nucleated films.

Accomplishment—We have obtained, for the first time, both the functional dependence of the mean tensile stress on island radius, and the absolute magnitude of the stress during island coalescence. This was accomplished by measuring stress changes during electrodeposition of Ni islands where the coalescence process was constrained via lithographically-defined island nucleation sites and selective-area growth (Fig. 1). As shown in Fig. 2, by systematically varying the radius of the coalescing cylindrical islands over two and a half orders of magnitude, we demonstrated that the experimentally measured initial coalescence stress is in good

agreement with the predictions from the recently developed Hertzian contact model of Freund and Chason (FC) [J. Appl. Phys. **89**, 4866 (2001)] and also with our two-dimensional finite element (FE) analysis. This agreement confirms that all of the dominant physical mechanisms in the initial island coalescence process are known and accounted for in the FC and FE models. Moreover, we have also determined that the initial coalescence stress is a minority component of the total stress created during the coalescence and planarization of the film. This striking result had not been previously observed in unpatterned metal films due to the inability to differentiate the stress created at the initial contact from that created during planarization.

Significance—The majority of thin films currently in use grow via an islanding mode, which invariably results in a tensile component in the stress. As the dimensions of these islands decrease into the nanometer regime, the coalescence stress can exceed a gigapascal, which impacts the effective materials properties. Therefore, the understanding of the stress evolution during the ubiquitous island coalescence process is crucial for nanotechnologies. This work provides the foundation for understanding the physical processes active during the initial coalescence of islands and lays the groundwork for future analysis of the post-contact stress generation process, which is considerably more complex. This understanding will help make more reproducible microsystems from electrodeposited metals – like the components formed in precision molds by the LIGA process and metal MEMS structures used in RF communications.

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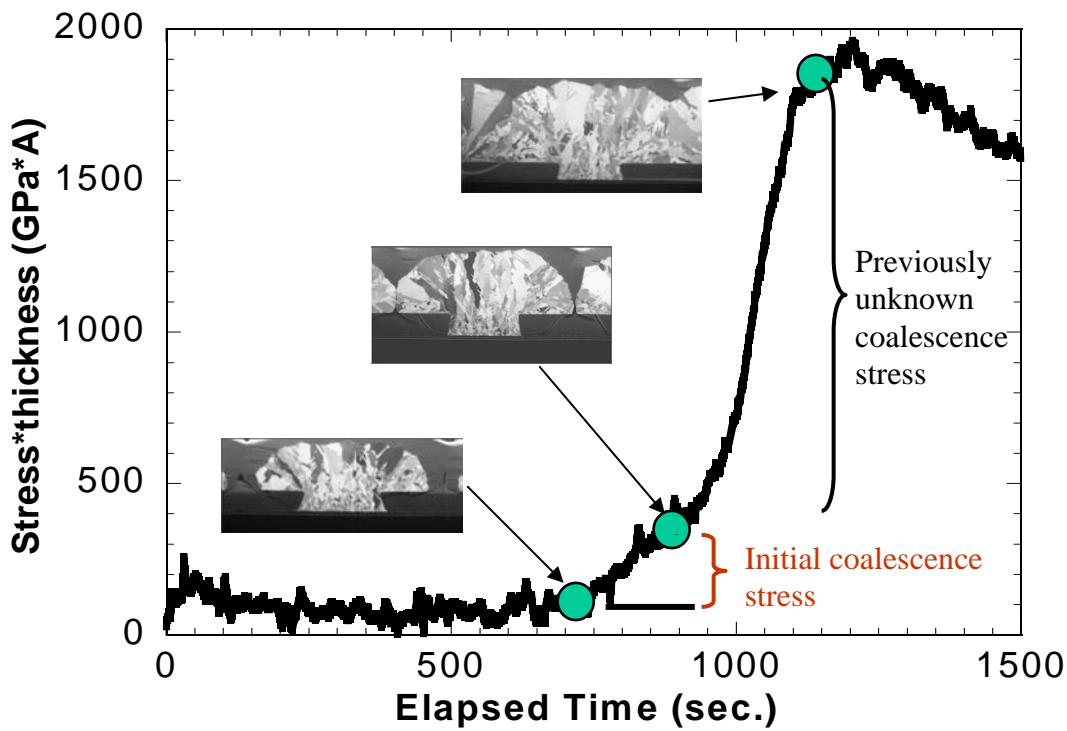


Figure 1. Plot of the stress evolution observed during electrodeposition of Ni onto a patterned substrate. Insets are cross-sectional focused ion beam (FIB) images of islands during the pre-coalescence, initial coalescence, and planarization stages of growth.

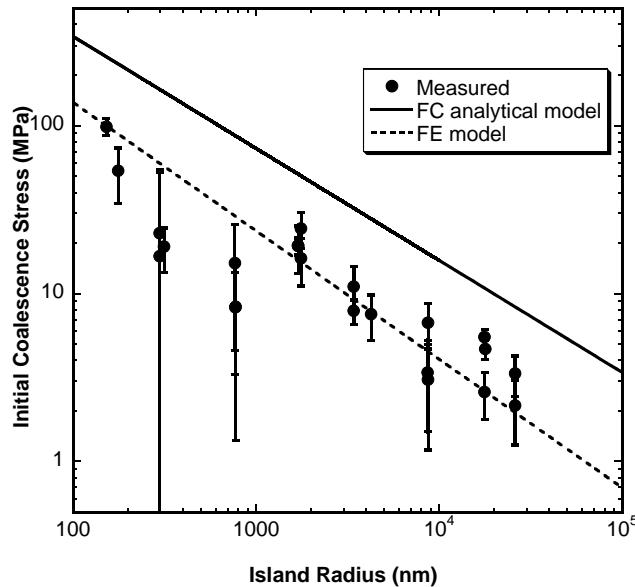


Figure 2. Plot of measured, Freund-Chason Hertzian contact (FC), and finite element (FE) calculated island coalescence stress as functions of radius. The plot demonstrates the excellent agreement between theory and experiment over two orders of magnitude.